A 106-d period in the nuclear source X-8 in M33

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ABSTRACT

With an X-ray luminosity of about $10^{39} \mathrm{erg} s^{-1}$, the source X-8 coincident with the optical center of M33 is the most luminous X-ray source in the Local Group. However, its nature remains a mystery. We present here new and archival ROSAT observations of X-8 spread over 6 years which show variability and a $\sim$ 106-d periodicity. This implies that (most of) the emission from M33 X-8 arises from a single object, perhaps a binary system with a ~ 10 $M_{\odot}$ black hole primary. We suggest that the companion is a giant orbiting with a $\sim$ 10-d period, and that the observed modulation is "super-orbital", analogous to that seen in Cyg X-2 and X1820-30.

Subject headings: Galaxies:individual:M33–Local Group–Galaxies:nuclei–X-rays:stars

1. Introduction

The nearby spiral galaxy M33 was first detected in X-rays using the *Einstein Observatory* Imaging Proportional Counter (IPC, Long et al. 1981) and the High Resolution Imager (HRI, Markert and Rallis 1983; Trinchieri et al. 1988). These observations revealed a bright source, X-8, coincident with M33's faint optical nucleus. The source comprised almost 70% of the total X-ray luminosity of M33. At M33's distance, 795 kpc (van den Bergh 1991), X-8 has a (0.15–4.5 keV) L_X of $\sim 10^{39}\,\mathrm{erg\,s^{-1}}$ and is the brightest source in the Local Group. Other observations of X-8 have been made using *EXOSAT* (Gottwald, et al. 1987), *ASCA* (Takano et al 1994), and the *ROSAT* Position Sensitive Proportional Counter (PSPC, Long et al. 1996) and HRI (Schulman & Bregman 1995). However, the nature of this source is still unresolved. Possibilities include a quiescent mini-AGN (Trinchieri et al. 1988; Peres et al. 1989), a collection of X-ray binaries (Hernquist, et al. 1991, hereafter HHK) and a new type of X-ray binary (Gottwald, et al. 1987).

The temporal properties of X-8 are likely to be crucial to unraveling the problem. However, not much has been known other than that the source was persistent at about the same luminosity over a 15 year baseline. Markert & Rallis (1983) did find (from *Einstein* HRI data) that the flux from X-8 had decreased by 40% on a time scale of six months, but similar variations were not detected in nearly simultaneous IPC and MPC observations. As a result, Peres et al. (1989) argued that the variability only affected energies below 1.2 keV. To address this problem, we have conducted a new study of the X-ray variability of X-8 based on *ROSAT* PSPC and HRI observations made between July 1991 and January 1997. Our results concerning the other bright sources will be published elsewhere.

2. Observations

Multiple *ROSAT* HRI and PSPC (0.1-2.4 keV) observations of M33 have been carried out (See Trümper, 1984, for instrumental details). The majority of these were centered on the optical nucleus of M33 at α $1^{\rm h}33^{\rm m}50\overset{\rm s}{.}4$, δ $30°39'36''$ (J2000), and even in the off-center pointings X-8 was in the field of view. In that period, the HRI and PSPC exposures totalled 387 ks and 62 ks respectively, of which 233 ks and 50 ks were centered on X-8 (see table 1). Some of these HRI observations, *rh20a* and *b*, were analyzed by Schulman and Bregman (1995) and some of the PSPC observations, *rp23a*, *b* and *c*, were described by Long et al. (1996), but the remainder have not been discussed previously. X-8 appears as a point source in all of the images. The point source is superposed on low surface brightness diffuse emission extending throughout the region around the nucleus, as has been described by Schulman & Bregman (1995).

To study the X-ray properties of X-8, we extracted counts from a $1'$ aperture centered on X-8 and estimated the background from a source-free annulus (with inner and outer radii of $2\overset{'}{.}8$ and $4'$) centered on X-8. The HRI data were extracted initially as barycenter-corrected photon arrival times, subsequently binned per orbit (defined as the average flux in good time intervals within 3000 s of each other, the average time when M33 is continuously viewable by *ROSAT*). The rates were then corrected for vignetting and background using the HRI point spread function (David *et al*, 1996). This made it possible to compare centered and off-centered fluxes. (The vignetting correction for the HRI was in fact quite small, <5%.) A similar technique was used for the PSPC data, but we only used the three off-axis PSPC observations individually, as correction uncertainties made comparisons between them impossible. The average corrected HRI and PSPC count rates were about 205 ks^{-1} and 580 ks^{-1} (compared to background rates of 15 ks^{-1} and 5 ks^{-1}), respectively.

3. Analysis and Results

We processed the data in three different formats: event lists, corrected mean orbital fluxes, and corrected mean observation fluxes. The photon arrival times were tested for variability using the Kolmogorov–Smirnov (KS) and the Cramer–Smirnov–von Mises (CSM) tests. We searched for power at frequencies between 10^{-3} and 10 Hz using a modified Fourier spectrum (Dubus et al., 1998) and for variability time scales following Collura et al. (1987). On corrected mean fluxes, we applied the standard χ^2 test and the Lomb-Scargle (LS) normalized periodogram. We also tested the corrected mean fluxes for variability using the method of Maccacaro et al. (1987).

The analyses were applied independently to each observation and to various combined datasets : *rh8* combines *rh83* to *rh60a* (taken over 2 contiguous weeks), *cen-h* combines all centered ($\leq 1'$offset) HRI observations, *hri* has all the HRI data, and *cen-p* contains all centered PSPC observations. The data were combined both as mean orbital fluxes and observation averages, except for *rh8* where only orbital means were combined. We did not attempt to include the 10-ks off-centered PSPC data into a single set nor to combine HRI and PSPC data. Tests on (uncorrected) arrival times were not applied to data combining on and off-centered data.

Within single orbits, the KS and CSM unbinned tests indicated time variability in three of the PSPC observations. Further analysis using the technique described by Dubus et al. (1998) revealed significant power at period of about 400 s. Thus, the short term variability that we observed is due to the 400 s 'wobble' used standardly during *ROSAT* observations to reduce spatial variations in the detector response. As might be expected, in observation *rp23c* when the amount of 'wobble' was reduced, there was no significant power at 400 s. Averaging the flux on spacecraft orbits eliminates this effect. Significant peaks were not found in power spectra of the on-axis HRI data, with an upper limit of 20% (15%

with the on-axis PSPC data) on any sinusoidal modulation at these frequencies (Dubus et al., 1998). Hence, the *ROSAT* data did not reveal any short term variability in X-8.

Within individual observations, X-8 is also fairly constant. The only exceptions were for *rp23c* when the flux increased by $\gtrsim 10\%$ in a few hours and *rh11a* when the flux may have decreased by $\gtrsim 10\%$ within a few days. The variations in count rate in *rp23c* were seen both in the soft (< 0.84 keV) and hard (> 0.84 keV) bands. This was also true if the boundary between soft and hard was set at 1.2 keV.

X-8 does appear to be variable in *rh8* (which combines *rh83*– *rh60a*). This is the best sampled time interval with an exposure time 163 ks time over 2 weeks (figure 1). We believe that the erratic behavior of X-8 during this time interval (figure 1) is real: (1) The on-axis observation is consistent with this hypotheses. (2) The background represents at most 10% of the raw flux while there are $\gtrsim 20\%$ variations. (3) Removing observations *rh85* and *rh87* (the furthest off-axis) or (4) changing the extraction regions has no effect. And (5) similar variations were observed neither in the background nor in any other bright source in the field of view.

When observations over long time intervals ($\gtrsim 1$ week) are considered, variability becomes far more obvious. As shown in figure 2, X-8 varies by $\gtrsim 20\%$ on a timescales of months. There are no reports of changes in the instrument sensitivity that could explain such variations. The PSPC data are included by assuming that the mean fluxes from the temporally close (within 10 days, see table 1) observations *rp232* and *rh20b* were the same and renormalized accordingly. PSPC and HRI data were *not* grouped together for analysis.

When a LS analysis is carried out on the long datasets, a 106-d period is found with very high confidence in the HRI data. The LS analysis was confirmed with other methods contained in the STARLINK PERIOD package: CLEAN, χ^2 fit to a sine wave and phase dispersion minimization (PDM) methods. All yield a period of 105.9 ± 0.1 days. The data

folded on the 106-d period are shown in figure 3. With this period, the erratic behavior in dataset *rh8* can be associated with the rise time at phases 0.8-1.0. The folded renormalized PSPC data fits in very well, although it does not separately reveal a 106-d periodicity, due, at least in part, to the fact that there are so few PSPC observations.

The period is also found in the centered observations alone, whether background-corrected or not, and as such, is not an artifact of the corrections and/or pointings. Removing each observation in turn to see if the detection is due to one in particular, we find either a $\sim$ 52-d or a 105.9-d peak whenever there is a sufficient time base. The alias at $\sim$ 52 days is ruled out by the last HRI observation *rh03* (obtained at phase 0.40-0.45, figure 3). The associated background showed no structure when folded on the 106-d period, and exhibits no variation greater than 10% of the amplitude of the X-8 modulation.

Simulating the X-8 data with a constant Poisson flux at the same mean gave no significant peaks in the LS analysis. Also, colored noise is unlikely at such low frequencies. While active galactic nuclei have a red noise power spectrum above $\sim 10^{-5}$ Hz, white noise dominates below that (McHardy 1988). The robustness to different changes in the data, the amplitude of the signal, the good phase coverage and the fit of the PSPC data all testify in favor of the reality of this periodic behavior.

For completeness, figure 3 also contains the folded mean fluxes of the 3 *Einstein* HRI and 2 IPC observations as given by Peres et al. (1989). (Details of the cross calibration between the *Einstein* HRI and IPC can also be found there.) Our renormalisation to the *ROSAT* HRI count rate is arbitrary. Despite the normalization uncertainties, the *Einstein* HRI data appear consistent with the 106-d period. One of the IPC points may be discrepant, but with only two measurements this discrepancy could easily be due to the difficulties associated with normalization. There were simply not enough *Einstein* observations to obtain a robust result.

4. Discussion

Although X-8 is the brightest X-ray source in the Local Group, the nucleus of M33 is optically inconspicuous and semi-stellar (Kormendy and McClure,1993, hereafter KM), with a core radius ≤ 0.3 pc and a low velocity dispersion of about 21 km s^{-1}. This implies a central relaxation time $\sim 10^7$ years. Thus, it is likely that the nucleus has undergone core collapse. HHK suggested that the M33 nucleus resembles a globular cluster and that the intense X-ray emission is due to $\sim$ 10 low mass X-ray binaries (LMXBs) formed during the core collapse, each with a luminosity of $\sim 10^{38}$ $ergs^{-1}$. (As noted by HHK, this requires sources brighter by a factor ten than galactic globular cluster LMXB sources).

A 106-d period renders this scenario unlikely. A 10% amplitude for the X-8 periodic variations requires that one of the ten objects modulates its luminosity by almost 100%, i.e. that it is transient. But this poses several problems: (a) This would be by far the shortest known transient recurrence time; (b) the quiescence interval would be extremely short; and (c) the outburst regularity would be exceptional. X-ray transients such as the neutron star LMXB Aql X-1 or the black hole candidate 4U1630-47 show outbursts on *timescales* of a few hundred days but are not periodic (Kuulkers et al. 1997). The detection of the 106-d period over $\sim$20 cycles implies a regularity and a short duty cycle incompatible with typical soft X-ray transients. We conclude that most of the X-8 luminosity arises from a single object.

One possibility is that the M33 nucleus contains a quiescent AGN. However, KM's upper limit of 10^4 $M_\odot$ on the mass contained in the inner 0.3 pc of M33 rules out the presence of a supermassive black hole and makes interpretation of X-8 as a quiescent AGN untenable. This conclusion is further supported by the *ASCA* (Takano et al 1994) and *EXOSAT* (Gottwald, et al. 1987). X-ray spectra of X-8, which are best described by a power law plus an exponential cutoff above 2 keV, unlike known AGN.

On the other hand, core collapse could have lead to the formation of a stellar mass black hole (KM), with $L_X \sim 10^{39}$ ergs^{-1} corresponding to an Eddington limited 10 $M_\odot$ black hole accreting at $\dot{M} \sim 10^{-7}$ $M_\odot$yr^{-1}. The X-8 spectrum is softer than typical neutron star LMXBs, but comparable to LMXB black hole candidate spectra (Takano et al 1994).

In principle, the mass transfer could arise from the wind of a massive O–B star. But such stars are not expected in the globular cluster-like nucleus of M33 and hence are excluded. Alternatively, tidal capture in the core could form a system in which the companion is degenerate. In this case, $\dot{M}$ implies $P_{\rm orb} \sim 0.1$hr and the mass of the donor star would be ~ 0.1 $M_\odot$ (King 1988), similar to the globular cluster source X1820-30. This neutron star LMXB has a $\sim 20\%$, 176d "super-orbital" variation, the origin of which is unknown. However, as the time scale for angular momentum losses through gravitational radiation is close to 10^4yr ($\sim 10^6$yr for X1820-30), it is unlikely that we are observing a degenerate system in X-8.

A 106-d orbital period would be compatible with an evolved companion with a 0.3 $M_\odot$ helium core and a total mass of ~ 2 $M_\odot$ (King et al., 1997a). This would make it the longest known orbital period in an X-ray binary. But King et al. (1997a,b) have shown that such systems would certainly be transient and this is not observed here. To make the source persistent, one is led to orbital periods of $\sim$ 10d and inconsistent mass ratios close to unity.

The assumptions of King et al. (1997a,b) do not hold if the companion is massive enough. For instance, the transient GRO J1655-40 is a 7 $M_\odot$ black hole binary with a 2.3 $M_\odot$ companion and $\dot{M} \sim 10^{-7}$ $M_\odot$ yr^{-1} (Orosz & Bailyn 1997). The companion is probably crossing the Hertzprung gap, evolving to the giant branch, and this places GRO J1655-40 in a narrow transient strip in an otherwise persistent luminosity domain (Kolb et al. 1997). Following figure 2 of Kolb et al. (1997), it is thus conceivable to have a persistent source such as X-8 if the companion is a $\gtrsim 2.5$ $M_\odot$ giant with $P_{\rm orb} \lesssim 10$-d. We note that O'Connell

(1983) found evidence in the nucleus of M33 for an increased population of intermediate mass (2-5 $M_{\odot}$) stars as compared to the M31 nucleus or our galaxy.

The origin of the 106-d period is still a problem. Precession of a warped disk (Maloney et al. 1996) would lead to eclipses rather than a modulation. King et al. (1997a) used the van Paradijs (1996) criterion for instability, i.e. that a necessary condition for instability is that the disk temperature be somewhere in the disk below the hydrogen ionization temperature of 6500 K. The condition for stability is most stringent at the outer radius where the temperature is lowest. Irradiation of the disk by the central X-ray source can have a major influence on this temperature (King et al., 1997a). With a ~ 2.5 $M_{\odot}$ giant companion and $P_{\rm orb} \sim 10$-d, the outer disk radius would be much larger than in most binary systems and irradiation could be limited only to the inner parts of the accretion disk. Relaxing the van Paradijs criterion could allow instabilities to exist in the outer regions, leading to variability in the source, and possibly "super-orbital" modulation. This will be the subject of a future paper.

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Fig. 1.— Average corrected orbital fluxes for *rh8*. On-axis observation *rh60a* can be seen at $d = 947$. The χ^2 test gives a $< 0.1\%$ probability that this is consistent with a constant flux.

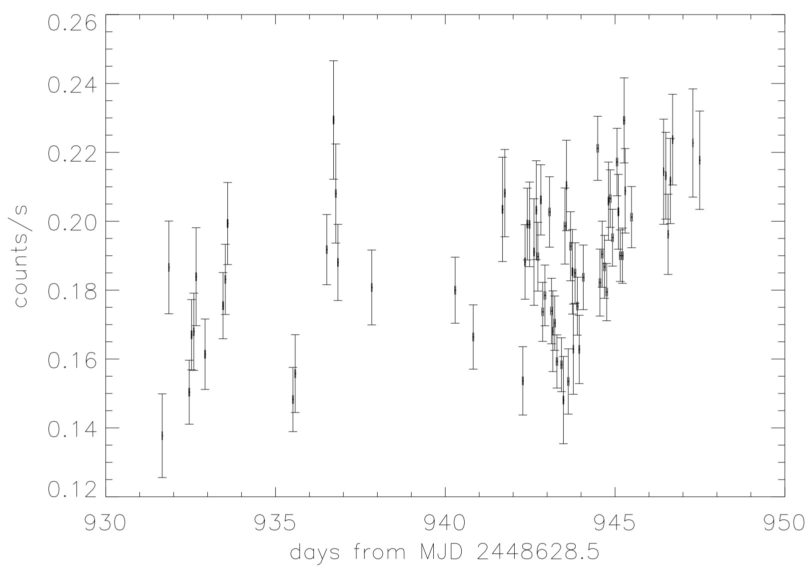
Fig. 2.— Long term lightcurve of X-8. Each point (HRI squares, PSPC circles) represents the average flux of each observation except at day$\approx$1000 which is the average of the off-axis observation + *rh60a*. The PSPC on-axis observations were renormalized as explained in section 3. The origin is the start of *rh20a*. Dotted line is the average HRI flux.

Fig. 3.— CLEAN power spectrum of the *hri* dataset (upper) and folded lightcurve of X-8 on 105.9 days (lower). The highest peak corresponds to the 105.9 day period (confidence >99.8%). Each point in the folded data represents the average X-8 HRI flux during one *ROSAT* orbit. The renormalized PSPC data appear as circles at phases 0.42 (*rp23a*,*rp23c*) and 0.05 (*rp23b*). The renormalized mean fluxes for the *Einstein* HRI (diamonds) and IPC (triangles) observation are also shown. The dotted line represents the average *ROSAT* HRI flux. The data are shown twice for clarity.

Table 1: *ROSAT* observations of M33

Obs.[a]	Offset (′)	Dates	Duration (ks)
PSPC			
*rp*23*a*	0	1991 29–30 Jul	29.1
*rp*23*b*	0	1992 10 Aug	5.0
*rp*23*c*	0	1993 7–9 Jan	16.3
*rp*07	17	1993 5–5 Feb	3.7
*rp*10	14	1993 5–6 Feb	3.5
*rp*89	12	1993 6–7 Feb	4.5
HRI			
*rh*20*a*	1	1992 8–12 Jan	19.1
*rh*20*b*	1	1992 1–3 Aug	15.8
*rh*83	14	1994 6–9 Aug	25.9
*rh*84	13	1994 8–9 Aug	18.7
*rh*85	16	1994 6–8 Aug	17.1
*rh*86	7	1994 1–11 Aug	16.4
*rh*87	17	1994 27 Jul–7 Aug	30.5
*rh*88	13	1994 27 Jul–7 Aug	24.5
*rh*89	10	1994 6–8 Aug	20.3
*rh*60*a*	0	1994 10–11 Aug	8.0
*rh*46	0	1995 15 Jan	24.6
*rh*60*b*	0	1995 10–16 Jul	40.9
*rh*11*n*	0	1996 18 Jan–8 Feb	46.4
*rh*11*a*	0	1996 17–27 Jul	44.6
*rh*03	0	1997 10–14 Jan	33.9

[a]The observation names correspond to the last digits of the *ROSAT* sequence numbers.



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0.22
0.20
0.18
0.16
0.14
0.12
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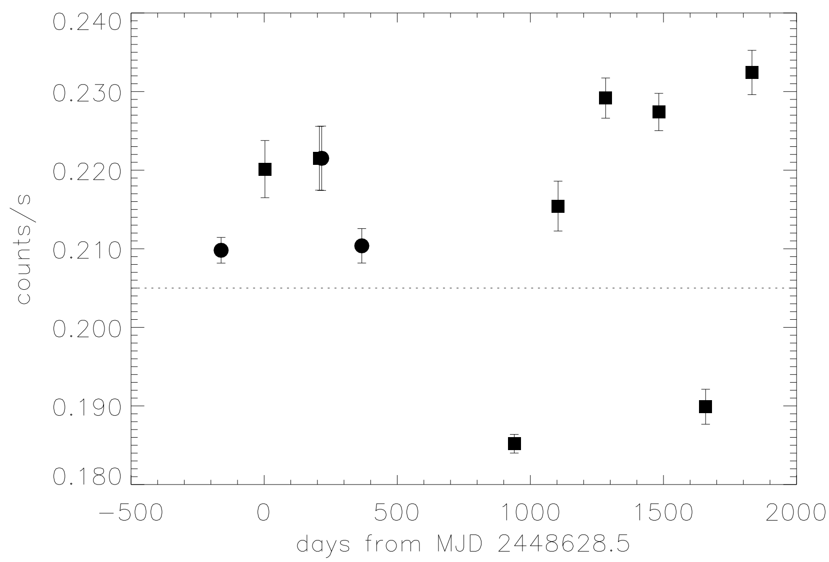
935
940
945
950
days from MJD 2448628.5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0.190
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counts/s
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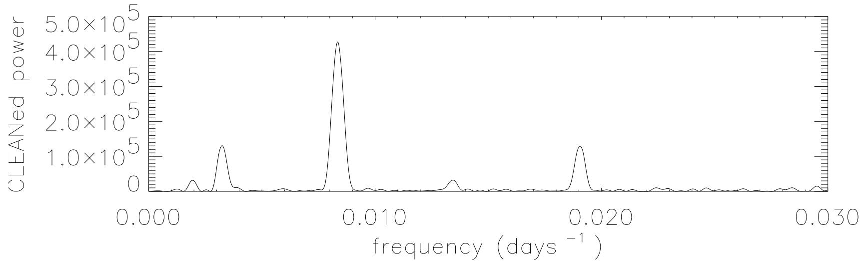
1500
2000
days from MJD 2448628.5


CLEANed power
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4.0×10^5
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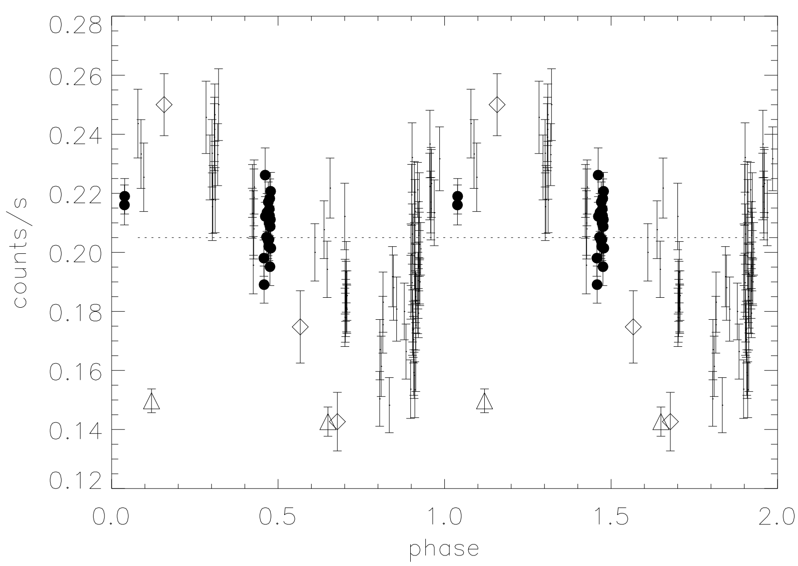
0.000
0.010
0.020
0.030
frequency (days^-1)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0.20
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1.0
1.5
2.0
phase